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NRL has recently completed an experiment in airborne gravimetry off the Southeast coast of the United States. This report describes the techniques of airborne gravimetry employed and the methods used to process and analyze the collected data. Results from the analysis of the study are presented.

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East Coast Gravity Validation Study

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Acoustics Media Characterization Branch
Acoustics Division

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CONTENTS

EAST COAST GRAVITY VALIDATION STUDY

INTRODUCTION

The Naval Research Laboratory (NRL) has recently completed an experiment in airborne gravity measurement off the southeast coast of the United States. The project was funded by the Naval Surface Weapons Center (NSWC). This report describes the techniques of measurement and analysis, and presents the results of the study.

The technology of stationary gravity measurements is relatively simple, consisting of determination of the amount of spring tension or magnetic force to support a known test mass. These measurements can be reliably made to nearly one part in one hundred million. Stationary measurements, however, are time consuming and expensive over land, and impossible at sea except in shallow water.

Gravity measurement from a moving platform or dynamic gravimetry adds several difficulties to the stationary problem. The test mass can no longer be completely stabilized because of the irregular motions of the platform. Instead, the motions of the mass are averaged over some time period and the supporting forces are varied as required to keep the mass within some limits of travel. This averaging changes the measurement from a point measurement to some spatial average of the gravity field along the track of the vehicle that depends on the averaging period and the velocity of the platform. Additional problems include the removal of the platform vertical accelerations from the measurement and maintaining the gravity meter level with respect to the local vertical frame of reference. This constant leveling is performed by gyro stabilization.

Vertical accelerations of the vehicle can be divided into two types. One type is due to changes in altitude with respect to the center of the earth. The other type is the vertical acceleration required to travel horizontally over a curved earth at a constant altitude plus the increase or decrease in centripetal acceleration of the vehicle caused by the addition of the vehicle velocity to the earth's rotational velocity. In the case of shipboard measurements the first type of acceleration is primarily caused by waves and, averaged over several minutes, is close to zero. At typical ship velocities a spatial average of less than 5 km is required to nearly eliminate vertical motion from the gravity measurement. The limiting factor on shipboard accuracy is generally determination of the second type of vertical acceleration. This is computed from the course and speed of the ship and is termed the Eotvos correction. Under ideal conditions and with excellent navigation shipboard measurements are accurate to within 1 to 2 mGal.

While shipboard measurements are accurate, ships are slow and expensive (per track kilometer) compared to aircraft. NRL began the development of an airborne gravity measurement system several years ago (Brozena, 1984). In addition to the difficulties of adequately determining the Eotvos correction (errors increase linearly and as square of velocity), the first type of vertical acceleration may no longer be simply averaged out. An aircraft is not constrained to move along a relatively constant surface as a ship is. This acceleration must be computed from an extremely accurate altimetry profile. The aircraft altitude must be known with an accuracy of a few centimeters.

Manuscript approved May 11, 1987.

The NSWC field experiment is the most recent effort in the NRL program to develop the technology of airborne gravity. The project was flown by the NRL Flight Detachment aboard one of NRL's research modified P-3 Orion aircraft. This is a 4 engine turboprop carrying a crew and scientist complement of 12 to 18 persons. The aircraft is well suited for airborne gravimetry with a long range (2600 nmi) capability at low altitudes. The NRL P-3 can handle more than 8000 lbs of equipment as well as full fuel and crew.

For this experiment, nominal altitude and speed were 650 m and 365 km/hr respectively. Data tracks, selected by NSWC, consisted of three profiles in a triangle. The tracks ran approximately from Charleston, SC to Jacksonville, FL to Cape Canaveral, FL and back to Charleston. Figure 1 shows the cross tracks added to the survey design to obtain crosstie points for least squares adjustments of the data. Most of the tracks were flown twice to fill in data gaps and to reduce random data error by averaging.

Figure 2 shows the prototype airborne gravity measurement system (AGMS) that consists of a LaCoste-Romberg gravity meter, a Global Positioning System (GPS) for navigation and Eotvos determination, and an extremely precise radar altimeter. Data from all sources are acquired and stored by onboard computer systems for postflight analysis. Background on the system hardware is available in Brozena et al., 1986.

SYSTEM DESCRIPTION

Gravimeter

The gravimeter provides the vertical component of acceleration. This includes the gravity signal along with vertical accelerations caused by aircraft motion. The gravimeter used for the experiment was a LaCoste-Romberg, air-sea meter, S-93, mounted on a three-axis stabilized platform. The meter and platform were refurbished in January, 1984. A cross-coupling calibration was performed at this time. The gravimeter outputs are recorded by a Hewlett-Packard (H-P) minicomputer system. Seventeen analog channels of data are scanned by a reed scanner and digitized by an A/D converter at a nominal 2-Hz rate. The channels of primary interest are the filtered beam position and the total cross-coupling. Unfiltered beam position signal is prefiltered by a 2-Hz cutoff, low-pass filter and acquired at a 20-Hz rate. Spring tension is digitally encoded by the meter and sampled by the scanner. The digitized data are formatted, blocked, and stored on disc and tape by the H-P 1000 minicomputer.

Altimeter

Altitudes are required for the free-air height correction and are needed to determine the aircraft vertical acceleration correction. The radar altimeter is a high-precision unit designed and built at NRL. The return of a narrow (< 2 ns) transmitted pulse is timed to an accuracy of approximately 0.2 ns. The radar is pulsed at a 10-kHz rate, and 100 returns are averaged for each output altitude. This procedure produces a 100-Hz radar altitude time series with accuracies of a few centimeters depending on sea state. The short transmitted pulse length means that the illuminated area on the sea surface is pulse-limited, rather than antenna beam-width limited. The area of interaction is only a few square meters of the sea surface closest to the radar antenna and within its 10° beamwidth. The altitudes are therefore unaffected by pitches and rolls of 5° or less. The nadir-looking transmit and receive antennas are located in the aircraft belly radome (Fig. 2). The spatial sampling rate at the nominal aircraft speed of 100 m/s is 1 m which should be sufficient to avoid aliasing of the aircraft heights with sea waves. The averaging of the radar data is done in real time by an intelligent interface designed by NRL which then transmits the averaged data to the H-P 1000 for blocking and storage. A complete discussion of the altimeter and interface design is included in Brozena et al., 1986.

Navigation

Horizontal positioning and velocity data for Eotvos and latitude corrections were provided by the Texas Instruments HDUE GPS. This is a prototype, five-channel, two-frequency P-code receiver. The majority of the tracks were flown during periods of coverage by four satellites. Except in cases of extremely bad satellite geometry root mean square (rms) errors should be less than 15 m for position and 15 cm/s for velocity. Position and velocity data reports are updated every 0.6 s and 1.2 s respectively. The GPS data were blocked and stored by the H-P 1000 to disk files for postflight analysis. The GPS real-time position readout was used to update the Litton-72 inertial navigation unit prior to the start of each data track. Since the inertial was interfaced to the autopilot, this procedure ensured that the track flown was relatively close to the desired track.

EXPERIMENTAL PROCEDURE

Five data flights were flown out of Patuxent River Naval Air Test Center (PAX NATC) on 26, 27 28 March, and 2,3 April 1986. We had approximately 5.5 h of GPS satellite coverage from 2230L to 0400L. Transit from Pax NATC to the operation area required about 90 min, therefore takeoff and landing were at 2100L and 0530L. Typical aircraft speed and altitude in the operation area were 365 km/hr and 650 m. The sequence of operations required for a typical flight is listed below:

- Ensure that the meter has maintained thermostating temperature since the last flight on battery or auxillary power.

- Take ground gravity measurement prior to engine start to determine meter drift rate.

- Attempt to maintain stable platform level in the 18 min damping mode through engine start, power shift and transit to the survey area.

- If system level was lost prior to start of a data track, fly in a straight line until level is regained.

- Compute and manually dial in the estimated gravimeter spring tension before each data track from the predicted ground speed, track, latitude and altitude.

- Take ground gravity measurement at end of flight.

- Connect gravity meter to battery for ground temperature control.

The weather during the flights was generally good over the northern portion of the operating area and poor over the southern region. A persistent low pressure zone remained centered near Cape Canaveral for all data flights. We experienced considerable turbulence in this area, although the aircraft accelerations seemed to remain within the dynamic range capability of the LaCoste gravimeter. The data on these sections of the tracks did not appear significantly worse than the data to the north.

Data were lost on several tracks, or portions of tracks for various reasons. The data acquisition computer occasionally halted, and several minutes of data were lost each time this happened while the computer system was rebooted. The GPS receiver also malfunctioned intermittently, creating gaps in the reduced gravity files. Several data gaps were caused by detours around thunderstorm cells. However, we planned sufficient flight time to fly each track at least twice. There were no data gaps remaining in the final data set and all segments had been flown twice with the exception of the northern end of the track from Charleston to Jacksonville and two of the crosstracks.

DATA REDUCTION AND ANALYSIS

Altimetry

The analysis of the altimetry data proved to be a difficult task because the intelligent interface system experienced a subtle failure. The time tagging of the data was occasionally scrambled and unrecoverable. Fortunately, the second derivative of the radar altitudes appears similar enough to the beam velocity measurement of the gravimeter that we were able to correct the altimeter timing by cross-correlating the two data sets. The lags of maximum cross-correlation for 1 min data segments provided corrections to the radar times. This procedure was effective but time consuming and probably increased the final reduced gravity measurement error slightly. After the altimetry series was time corrected, the data were filtered commensurately with the Lacoste filter and numerically differentiated twice to produce the vertical acceleration correction. The filtered heights are also used in the vertical gradient free air altitude correction. See Fig. 3 for altimeter geometry and the gravimeter land station tie.

Navigation

The GPS data require relatively little processing. The latitude, longitude and velocity data are stored on disk files. These files are edited for bad positions and velocities which sometimes occur when switching to a new satellite or in cases of extremely bad geometry. The velocity data must also be filtered with the digital equivalent of the three-stage 20-s time constant filter. Eotvos corrections are then calculated from the velocity data in the edited files and the standard gravity is obtained from the latitude.

Gravimetry

Spring tension, cross-coupling and beam velocity are abstracted from the gravimetry tapes. These values are splined to equal time spacing and the proper scale factors for meter S-93 are applied. The spring tension is filtered to match the beam velocity and cross-coupling, and the resulting data are combined with the processed navigation and altimetry. The resulting raw gravity values are filtered backwards in time to remove phase-lags caused by the forward filtering. A digital zero phase-lag finite impulse response (FIR) filter was designed to have a cutoff wavelength of approximately 20 km to further reduce the noise in the processed data. Profiles that extended outside the survey area received one or more passes of the filter which eliminated about 1 min of data from the start and end of a profile. The effect of multiple passes of the filter is to increase the sharpness of roll off.

After filtering, multiple overlying data tracks were averaged to produce a single set of gravity profiles for the triangle and cross-tracks. A least squares adjustment to minimize mis-ties at the track intersections was then performed. This program assumes a linear error model for the individual tracks and determines the constant and slope of a correction to be applied to each track. The averages of the values from the intersecting tracks at the three corners of the survey triangle are used to constrain the minimization. After the least squares corrections were applied, the average and rms mis-tie with regard to sign were -2.0 and 3.9 mGal respectively. Without regard to sign the mean and rms were 3.2 and 4.3 mGal (Fig. 4).

Final data sets were produced with a data point spacing of approximately 2 km. Figure 5 is a plot of the free-air anomaly data profiled along the perimeter tracks on a mercator projection. Figure 6 shows some of the free-air data plotted as annotated tracks. Figure 7 shows the data from all tracks gridded to produce a contour map of the region which was made at the request of NSWC.

This map may contain regions with considerable error as there are contours drawn over areas that are not within 35 km of any data. The defined purpose of the study was to produce gravity data along the perimeter tracks, however, the cross-tracks also produced useable data, perhaps of slightly lower quality.

GROUND TRUTH ANALYSIS

The data presented in Figs. 5, 6, and 7 are free-air gravities anomaly reduced to sea level by application of the 0.3086 mGal/m altitude correction to the data taken at altitude. Digital tapes of the the data were supplied to NSWC for comparison to ground truth data. These tapes included latitude, longitude, altitude, total gravity value (tied to the Patuxent base station on the International Gravity Standardization Net IGSN 71 network) at altitude and reduced to sea level, and the free-air gravity anomaly calculated at sea level with reference to the International Association of Geodesy IAG 1967 theoretical gravity formula. Tables 1 to 4 show the results of the NSWC comparison.

The mean difference for the perimeter triangle between the NRL airborne and the NSWC shipboard data is under 1 mGal and the rms is about 3.7 mGal depending on the method of comparison. As we expected, the data for the crosstracks has slightly greater error since there was less redundant data. A reasonable estimate of the accuracy could attribute 0.5 to 1 mGal of the rms discrepancy to the surface data. We also believe that several tenths of a mGal of error in the airborne data occurred because of the timing problems of the radar altimeter. Overall, the system accuracy seems to be in the 2.5 to 3 mGal rms range. This is consistent with previous determinations of the accuracy of the airborne system (Brozena and Peters, in press). The nature of the airborne gravity system will also produce less rms error for surveys designed as a tighter grid than the one shown here. Producing profile data along single tracks is a worst-case scenario for gravity surveys. It is also important that there does not seem to be any significant amount of bias or mean error in the system.

CONCLUSIONS

The results of the airborne gravity experiment indicate that the system is capable of producing detailed and self-consistent surveys rapidly and relatively inexpensively. Analysis of crossovers indicates a rms mis-tie of about 4 mGal. Comparison with ground truth data indicate rms errors of about 3.6 to 3.8 mGals with no appreciable bias. Some of this difference can be attributed to errors in the ground truth data. The system should still be considered a prototype needing development in both hardware and software, but we believe that the results presented here demonstrate the merit of developing and transitioning this system to the surveying community.

ACKNOWLEDGMENTS

We thank Gary Sitzman of NSWC for his support of this program both in funding and encouragement. We also thank Henry Fleming of NRL for his continuing support of the airborne gravity program. We especially thank the Navy personnel who fly and maintain the NRL aircraft, who work long hours to produce successful airborne projects. Sandy Vermace performed much of the computer data reduction and analysis for this project.

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J.M. Brozena, "A Preliminary Analysis of the NRL Airborne Gravimetry System," *Geophysics*, **49**, 1060-1069 (1984).

J.M. Brozena, J.G. Eskinzes and J.D. Clamons, "Hardware Design for a Fixed Wing Airborne Gravity Measurement System," NRL Report 9000, 1986.

J.M. Brozena and M.F. Peters, "An Airborne gravity Study of Eastern North Carolina," *Geophysics*, in press.

Table 1 — NRL Total — NSWC Total

	n	Mean	Std Dev (mGal)	rms	Min	Max
All points	929	−0.77	4.08	4.15	−13.45	17.98
Triangle	510	−0.23	3.61	3.62	−13.45	8.70
Crosstracks	419	−1.42	4.51	4.72	−10.32	17.98

Table 2 — Comparison of the NRL Geodetic Reference System GRS 67 Anomalies at Altitude to the NSWC Data at Altitude Computed from GRS 67 Surface Anomaly Data + GRS 67 Oblate Gravity

	NRL Anomaly — NSWC Anomaly					
	n	Mean	Std Dev (mGal)	rms	Min	Max
All points	929	0.63	4.08	4.13	−11.93	19.14
Triangle	510	1.15	3.62	3.80	−11.93	9.59
Crosstracks	419	−0.02	4.51	4.50	−8.77	19.14

Table 3 — Comparison of the NRL Total Gravity at Sea Level to the NSWC Total Gravity at the Surface Computed from the GRS 67 Formula + Surface Anomaly Data Referenced to GRS 67.

	NRL Total — NSWC Total					
	n	Mean	Std Dev (mGal)	rms	Min	Max
All points	929	−0.87	4.27	4.35	−14.47	18.49
Triangel	510	−0.35	3.83	3.84	−14.47	9.14
Crosstracks	419	−1.50	4.67	4.90	−10.42	18.49

Table 4 — Statistics of Gravity Anomalies

	n	Mean	Std Dev (mGal)	rms	Min	Max
NRL Data	929	2.66	15.26	15.49	−34.90	36.80
NSWC Data	929	2.04	15.22	15.34	−32.71	32.03

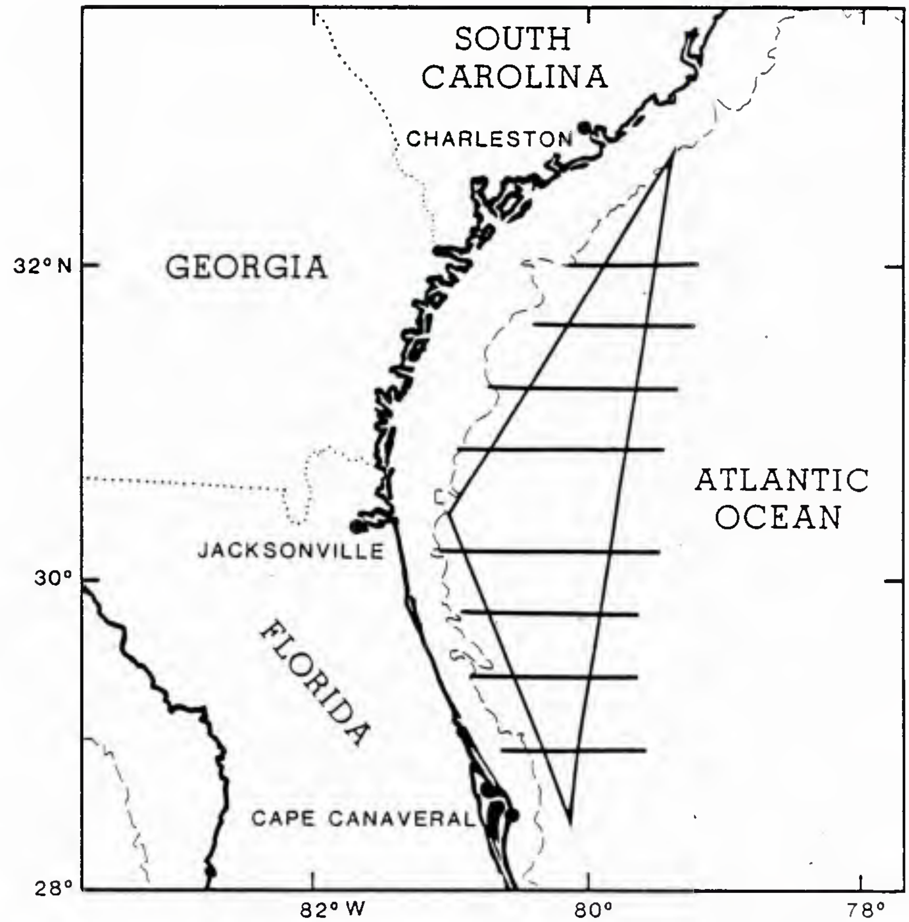


Fig. 1 — Track diagram of the East Coast Airborne Gravity Validation Study. The triangular tracks were specified as the study tracks by NSWC. NRL added the crosstracks to perform least squares profile adjustment and obtain crossover error statistics.

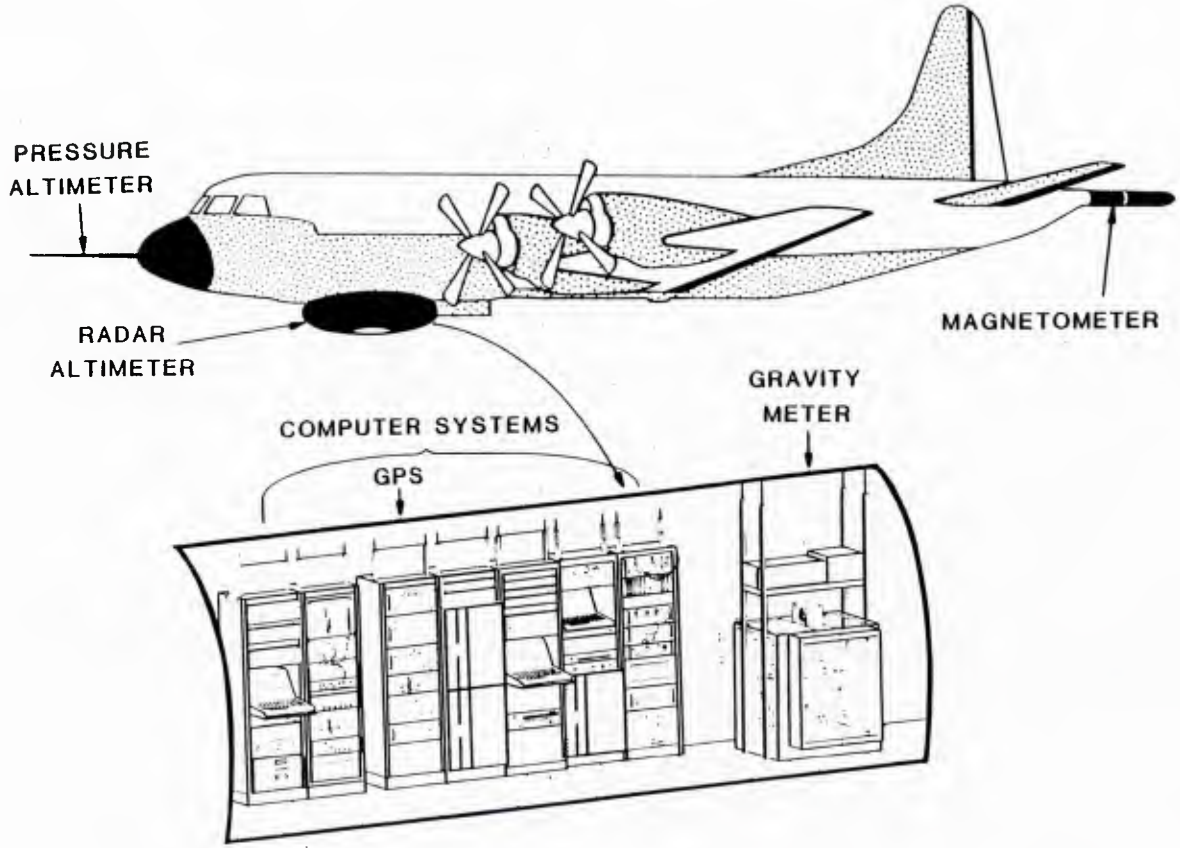
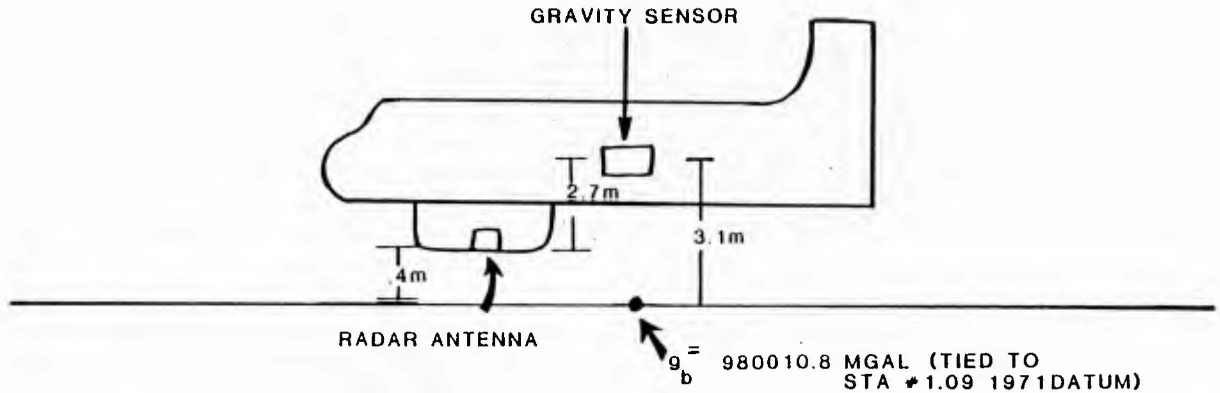


Fig. 2 — Cutaway view of the P-3A showing the airborne gravity measurement system including the gravity sensor, radar altimeter, GPS and data acquisition systems. The pressure altimeter was not required for this project since all flights were over water.

AIRBORNE GRAVITY SYSTEM GEOMETRY



AIRCRAFT METER READING AT BASE = 11387.5 MGAL

CONTINUATION TO GROUND = 1.0 MGAL

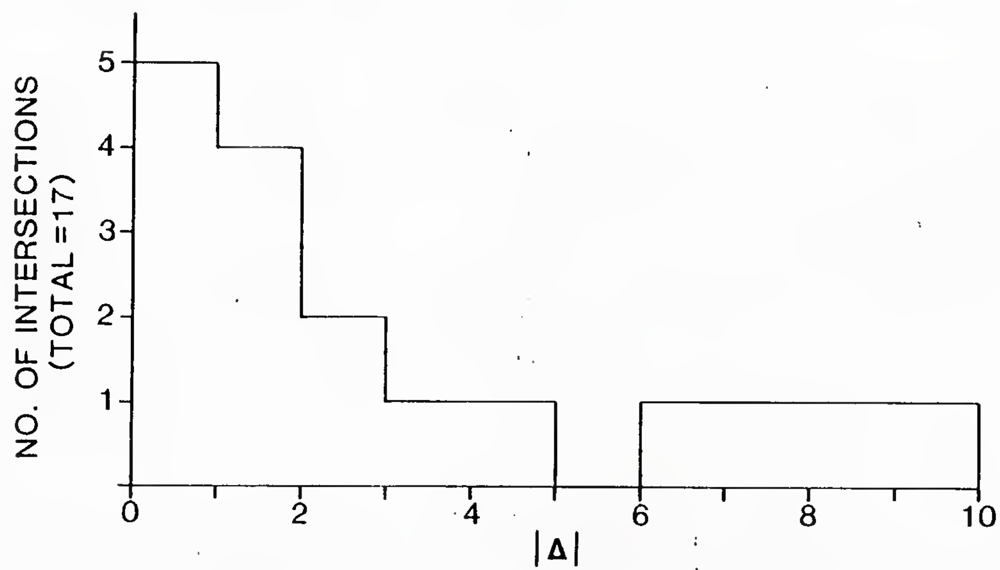
11388.5

METER OFFSET = 968622.3 & DRIFT

CORRECTION FOR UNCOMPENSATED ALTIMETER OFFSET
& HEIGHT OF METER ABOVE ANTENNA = -7.5 MGAL

Fig. 3 — Geometry of the radar altimeter and gravity sensor. Relative gravity measurements are tied to absolute measurements through a gravity base station at Patuxent River NATC.

JACKSONVILLE AEROGRAVITY CROSSOVER STATISTICS



$|\overline{\Delta}| = 3.2$ mGAL

$\left(\frac{1}{n} \Sigma \Delta^2\right)^{1/2} = 4.3$ mGAL

$\overline{\Delta\pm} = \overline{X_1 - X_2} = -2.0$ mGAL

$\left(\frac{1}{n-1} \Sigma \left(\Delta\pm - \overline{\Delta\pm}\right)^2\right)^{1/2} = 3.9$ mGAL

AVERAGE LENGTH OF TRACK BETWEEN INTERSECTIONS IS 63 KM.

Fig. 4 — Crossover statistics for the study

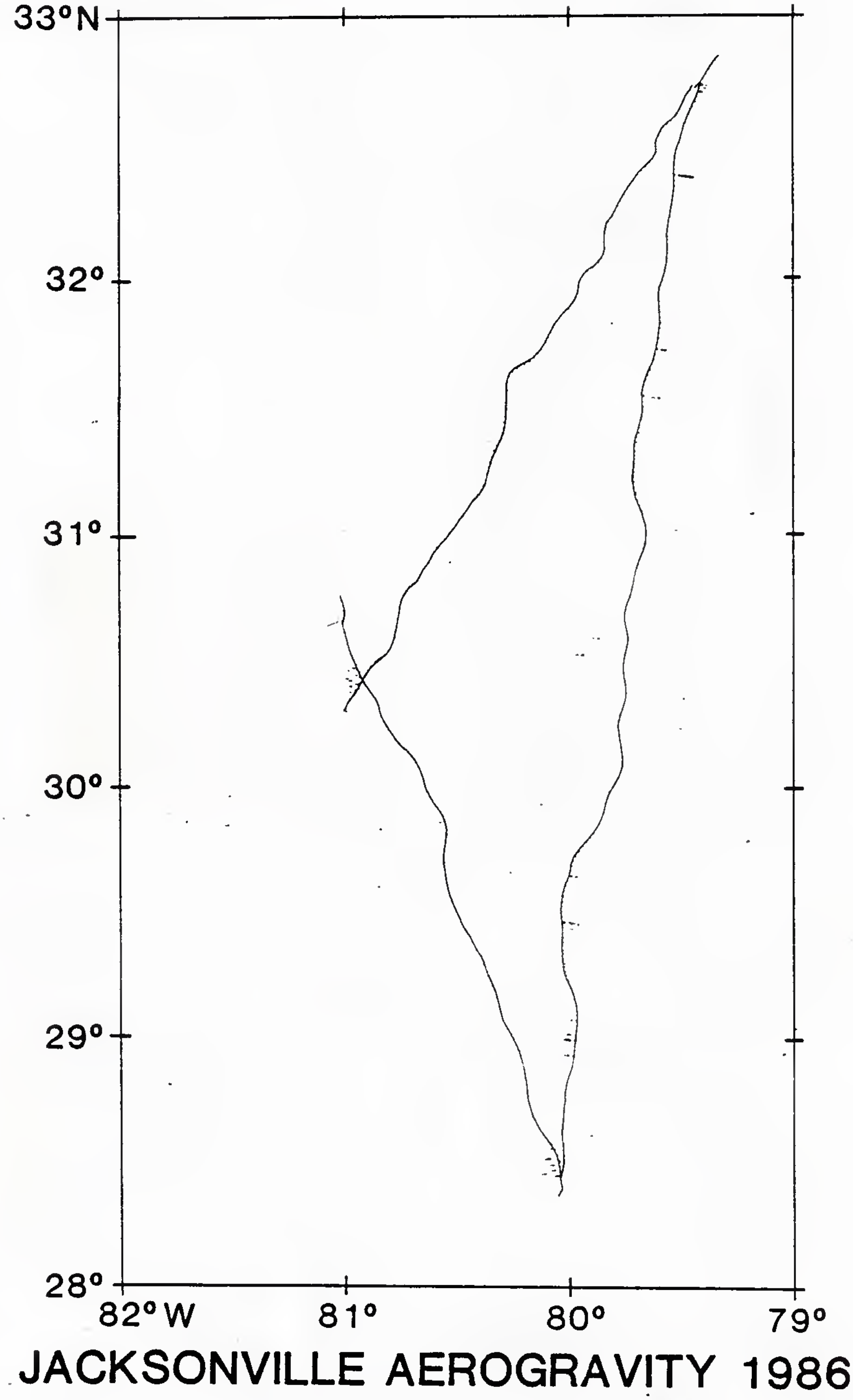


Fig. 5 — Sea level free-air gravity anomaly (GRS 67) plotted as profiles along the perimeter tracks on a Mercator chart

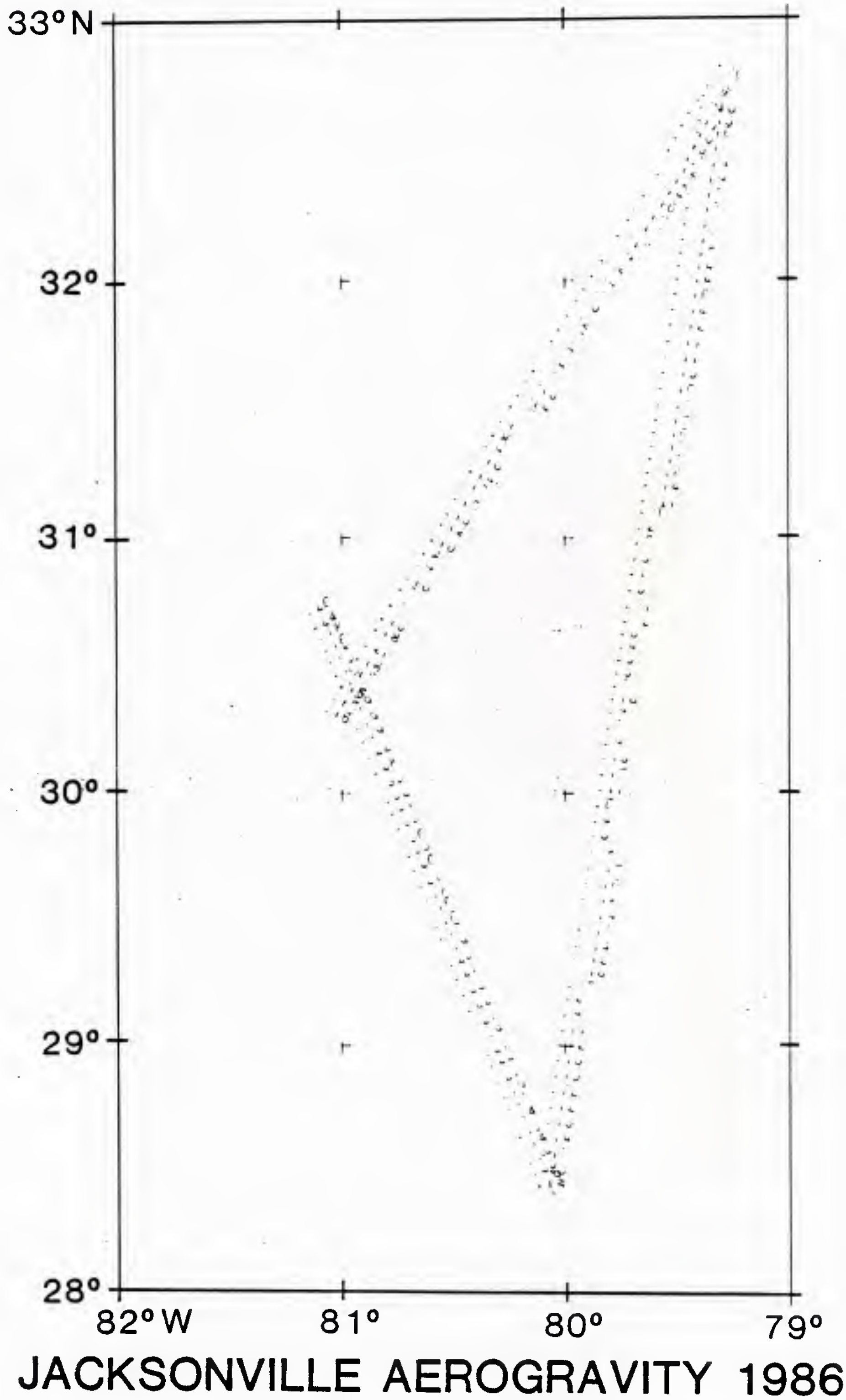


Fig. 6 — Sea level free-air gravity anomaly (GRS 67) plotted as annotated data along the perimeter tracks on a Mercator chart. Data are decimated for visibility. Actual data spacing is 2 km.

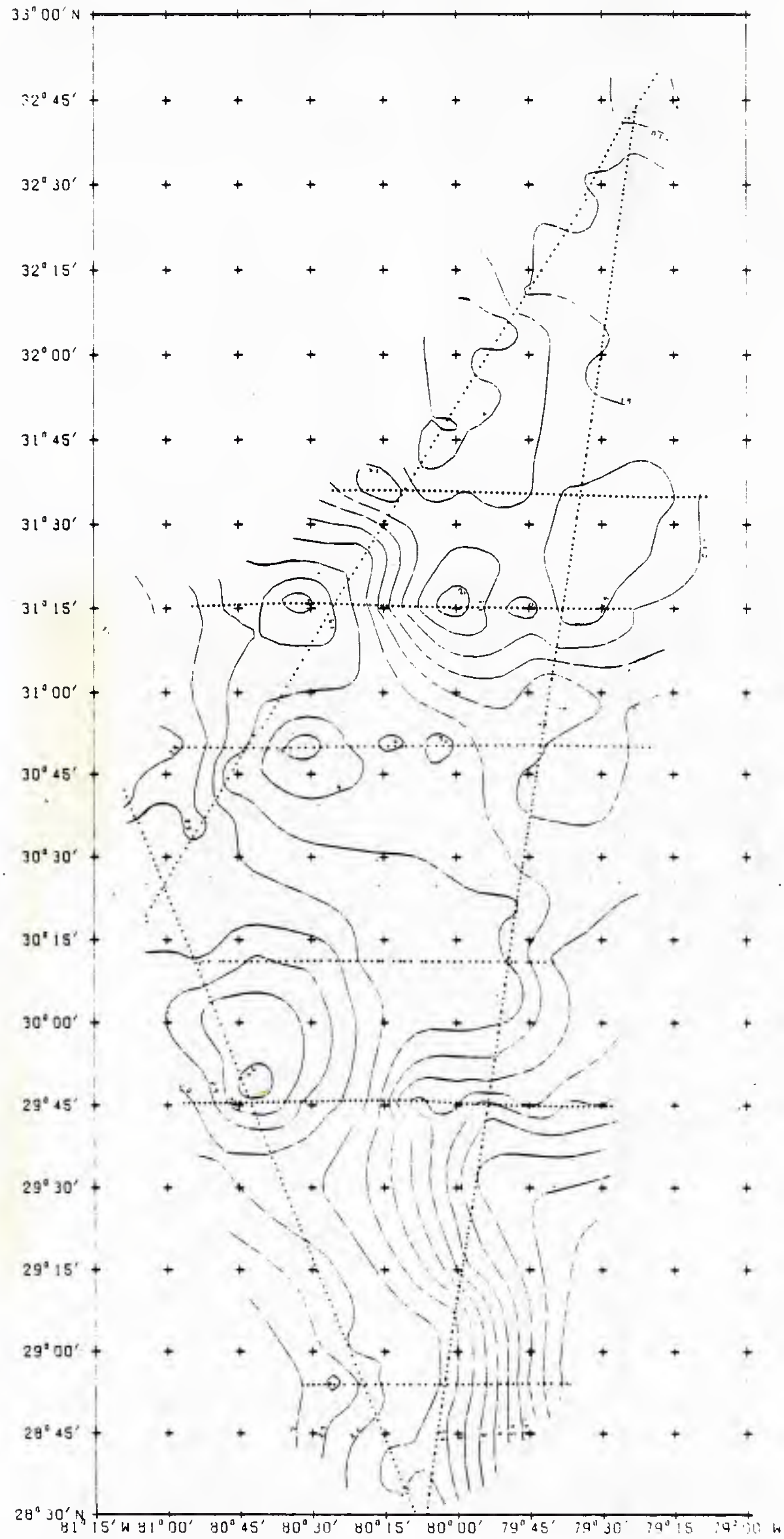


Fig. 7 — Sea level free-air gravity anomaly (GRS 67) gridded and contoured at a 5-mGal contour interval. This data set included the cross-tracks.

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